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SPECTRA OF SEISMIC WAVES FROM UNDERGROUND EXPLOSIONS FROM OBSERVATIONS IN THE NEAR ZONE

By

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FOREIGN TECHNOLOGY DIVISION

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SPECTRA OF SEISMIC WAVES FROM UNDERGROUND EXPLOSIONS FROM OBSERVATIONS IN THE NEAR ZONE

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SEISMIC INDICATIONS OF SUBSURFACE EXPLOSIONS DISCUSSED

[Article by N. V. Kuz'mina: "Spectra of Seismic Waves from Underground Explosions Observed in the Near Zone"; Scientific Technological Mining Society, Blasting, 1968, Issue 64, pp 240-261]

The seismic ground waves generated by industrial explosions affect various installations representing complex mechanical systems and possessing many degrees of freedom and a wide spectrum of natural oscillations [1]. In this connection the study of the ground oscillation spectrum at various distances from the focus of the explosion is a matter of considerable practical importance. Furthermore, a study of the basic natural laws governing the spectral composition will broaden our knowledge of the mechanism governing the activation and formation of waves.

A number of literary sources, such as studies [2-4] for example, deal with the effect of an explosion on the spectrum of excitable ground oscillations for frequencies from 1 to 10 hertz. But the spectral study of oscillations generated by industrial explosions in the mentioned frequency range, especially near the focus of the explosion, has not become widespread enough. This is due in large measure to the continuing lack of apparatuses designed to record the ground displacement in the near zone of the explosion.

The new seismic apparatuses [5-7] developed by the Institute of Physics of the Earth of the USSR Academy of Sciences, which are capable of recording ground displacements as small as 150 mm in 1.5-100 hertz frequency range with minor distortions, have made it possible to observe underground explosions set off by charges varying from tens of kilograms to a thousand tons several kilometers from the epicenter.

These observations were used to obtain the frequency spectra of the displacements with a view to studying the effect produced on the wave spectra by the distance from the explosion epicenter, and the depth and weight of the explosive charge. The spectral analysis data were also used in the search for objective criteria for the purpose of defining the near zone of the explosion — the zone of inelastic ground deformations.

The above-listed problems were accompanied by a comparison of the visible seismic wave periods with a frequency of the peak amplitude spectrum for such an asymmetric signal as the ground oscillation in the near zone of the explosion.

It should be pointed out that not all of the mentioned problems are adequately dealt with because of the few usable data. However, the accumulation of information on a frequency analysis of the seismic oscillations in each of these problems, especially near the explosion, is a point of interest, as the spherical radiator theory [8, 9] has to be experimentally tested, and there is still no theory of complex sources of seismic waves such as an explosion near the surface.

A description of the experimental material and the selection of a numerical recording area. An oscillogram resulting from the study of the seismic effect of effective explosions in Kazakhstan [10] and camouflet explosions in the Moscow area [11] was used for a spectral analysis.

The site on which the explosions were set off were of different geological structures. The upper layer of the cross section was characterized by a low speed of longitudinal wave propagation. Such layers are known in seismic prospecting as low velocity layers (LVL). The thickness of the LVL and the average propagation speed of the longitudinal waves in it are shown in Table 1.

Table 1

Explosion area	Explosion sites	Thickness of low velocity layer, meters	Rock	Ground density, g/cm^3	Average propagation velocity of longitudinal waves, m/sec
Kazakhstan	I	15-20	Silty loam	1.6	400-600
	II-III	6-7	Brown-green clay	1.9	Up to 750
Moscow Area	--	25-30	Morainic loam	2.0	300-500

The clearly defined seismic boundary is the underside of the low velocity layer. Underneath it, in Kazakhstan, lies the blue clay where the propagation speed of the longitudinal waves is $v_p = 2000$ m/sec and their density $\rho = 2$ g/cm^3, and in the Moscow area lies water-saturated loam of the same density and rate of $v_p = 1700$ m/sec.

The explosions were set off within the low-velocity layer and, on site II in Kazakhstan, in the contact area between the brown-green and blue clay. Amonite-6 was used as an explosive in a stope with an earth facing.

The recording of the ground oscillations produced by the explosions revealed that the oscillograms near the epicenter were very simple in form and consisted of two asymmetrical oscillations. The ground movements were manifested in the form of a dome-shaped uplift associated with the superposition of an elastoplastic compression wave and the slower effect of the gaseous explosion products.*

Inasmuch as the radius of the near zone, the depth of the charge and the distance from the explosion epicenter depend on the weight of the charge to the power of 1/3 [10], the spectra of all the explosions were compared on the same corrected distances of $\bar{r} = r/\sqrt[3]{q}$. The spectra near the explosion epicenter were calculated by the z and x component for the entire oscillogram. In this case the spectra of the total movement are indicated on the diagrams by letter K.

In a more distant explosion zone — $\bar{r} > 8$ m/kg$^{1/3}$ (Fig. 1, a, b) — the movement of ground particles acquires an oscillatory character on both components; in this case the longitudinal body wave p is recorded in the first inlet region from the underside of the low-velocity layer (the first upward maximum), and the following extremes (R_1, R_2, and so on) propagate at the phase velocity of surface wave R.

On the corrected distances $\bar{r} > 6 \div 8$ m/kg$^{1/3}$, where the longitudinal and surface waves diverged in time, the spectra were obtained separately for waves p and R (of the z-component).

In the case of ejective explosions, the ground displacement spectra were obtained for charges weighing 120, 1,000 (two explosions on sites I and II) and 10,000 kg at the corrected distances of 1.5; 2.5, 10; 20; 30 m/kg^3. These explosions were set off at the reduced depth of $\bar{h} = h/\sqrt[3]{q} = 0.42 \div 0.52$ m/kg$^{1/3}$. In the camouflet explosions at a depth of h = 2.7 m/kg$^{1/3}$ the oscillation spectra were calculated for the charges weighing 120, 300 and 1,000 kg at the reduced distances of 3, 4 and 10; 20; and 30 m/kg$^{1/3}$. A total of 75 spectra of K, p and R waves were calculated. The displacement spectra are designated by $|\bar{S}_i|^j$ whereby account is taken of the recording scale, or by $|S_i|^j$ with the scale left out of account. The j index designated the p, R or K wave. The spectra of the wave displacement speed were calculated by multiplying them by the angular frequency. The velocity spectra are designated in the same way except that index u is added at the bottom.

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*See article by B. G. Rulev and article by V. B. Lebedev and so on in this collection.

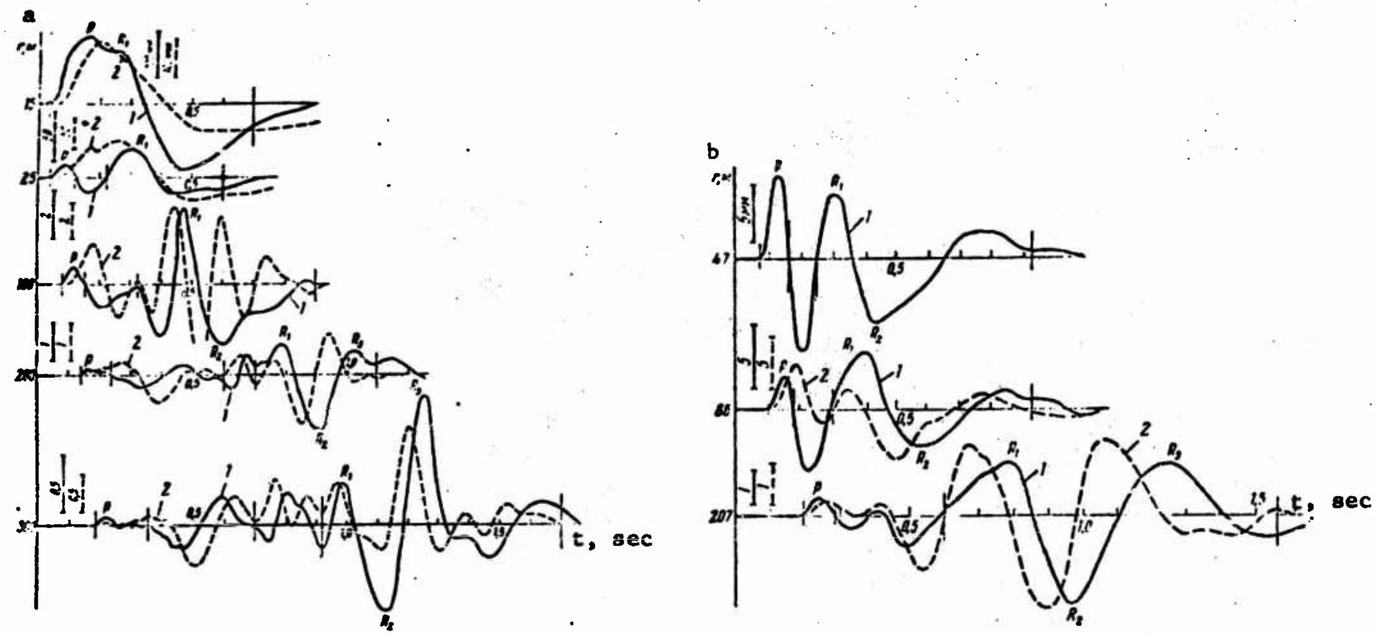

Fig. 1. Oscillograms of ground displacements at various distances from the explosion: a — ejective explosion in Kazakhstan (q = 1000 kg, h = 5 meters); b — camouflet explosion in the Moscow area (q = 1000 kg, h = 28.4 meters); 1 — z-component; 2 — x-component. The vertical lines indicate intervals for which the spectra were calculated.

The frequency spectra were calculated by a programmed computer [12]. Inasmuch as the recording duration of the p and R waves increases with the rising values of q and r, the length of the analyzed area changes accordingly. The recording duration of the dome-shaped ground uplift K increases with increasing q and decreases with the growing distance.

The recording duration of the p wave generated by ejective explosions in Kazakhstan and a number of other areas amounts to not more than a semioscillation, as the more intensive and low-frequency N wave [10] is eventually superposed and is followed by the Rayleigh-type surface wave R (see Fig. 1, a). The spectrum of the p wave for camouflet explosions in the Moscow area was also calculated for the first semioscillation, although there is no assurance of the validity of such an evaluation in view of the following intensive ground movement toward the explosion. However, if a whole cycle had been analyzed, it is possible that the error would have been still greater. Thus we know from study [13] that 75 percent of the seismic energy produced by the explosion is carried by the first semioscillation.

The recording duration of a surface wave amounts to 1-1.5 cycles (see Fig. 1, a, b) except in case of an explosion set off by a charge weighing 10,000 kg, whereby wave R consisting of an oscillation train is recorded [10]. In the latter case the area to be analyzed was set at 1.5-2 cycles, as a longer cycle produced a sharp decrease in the oscillation amplitude. An increase in the duration of the analyzed section of wave R by 0.1-0.2 sec (r = 200 and 300 m, see Fig. 1, a) led to a change of only 5-7 percent in the amplitude and frequency of the peak amplitude spectrum. Eventually, only the short wave pulse R with a duration of 1-1.5 cycle was analyzed.

A comparison of the visible periods of oscillation and the frequency of the peak amplitude spectrum. The spectra of the ground movement K and surface wave R are simple in form and have one pronounced peak in the frequency area of 1.5-4.5 hertz (Fig. 2). The amplitudes of the higher-frequency components are reduced by one order and more in comparison with the amplitude of the basic maximum.

A comparison of the resonant frequency of the spectrum and the visible recording frequency was made for the total K and R movement. Such a comparison cannot be applied to the p wave as the half-cycle spectrum has a peak in the zero frequency area [14]. The duration of the p wave in our experiments is one half cycle.

The data on the visible recording frequency f^{vis} and the frequencies corresponding to the spectral maximum f^{max} are cited in Table 2. This table also shows the appropriate T^{vis} and T^{max} cycles and the relative width of the cycle (on an 0.7 level). The visible cycle of the R wave was defined as a doubled half-cycle between the extremes, and in the case of the total ground K movement, based on the x- and z-components, as a quadruple

time of an increasing displacement to the maximum. It follows from the table that the visible recording frequency of the R wave is 20-30 percent higher and the ground K movements 30-50 percent higher than f^{max}.

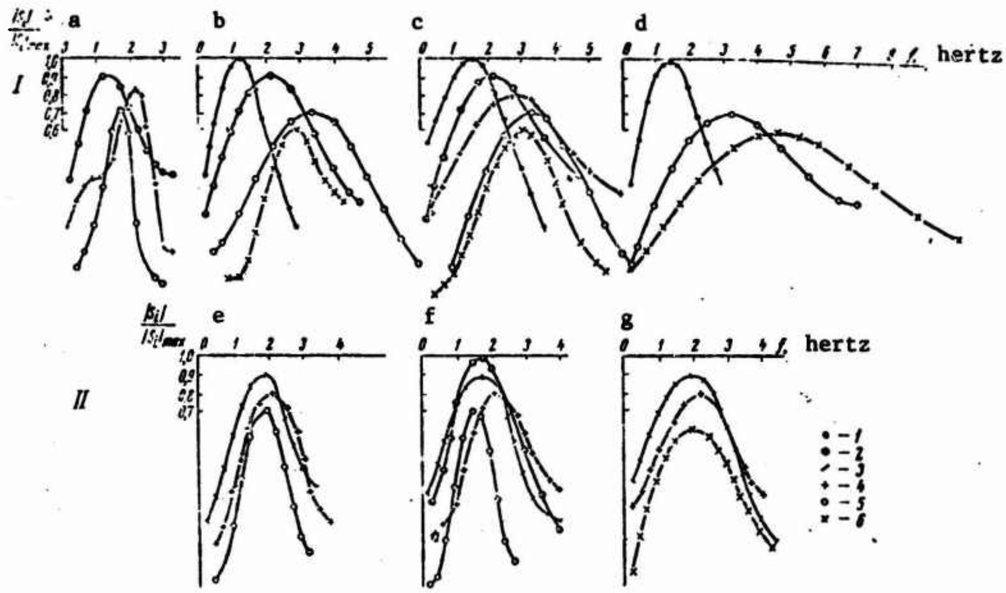

Fig. 2. The changing frequency spectra of surface wave R and total ground movement K depending on the corrected distance: I -- ejective explosions; II -- camouflet explosions; a -- q = 10^4 kg; b -- q = 10^3 kg (site II); c -- q = 10^3 kg (site I); d -- q = 120 kg; e -- q = 10^3 kg; f -- q = 330 kg; g -- q = 120 kg; 1 -- $\bar{r}$ = 1.5; 2 -- $\bar{r}$ = 2.5; 3 -- $\bar{r}$ = 4; 4 -- $\bar{r}$ = 10; 5 -- $\bar{r}$ = 20; 6 -- $\bar{r}$ = 30.

These data do not contradict the results of studies [15 and 16] the first of which shows that the maximum frequency of the spectrum does not coincide with the prevailing short pulse frequency in the form of sinusoid segments. The shorter the pulse, the greater the difference.

Thus the resonant frequency of the spectrum is a more objective and accurate characteristic of the asymmetrical recordings in the near zone of the explosion than the visual frequency determination.

The changing spectra of surface waves with distance and the ground movements in the epicentral region. The frequency spectra of the surface wave displacements and the K movement make it possible to follow the changing form of the spectrum and amplitudes of the spectral components with distance, as well as to outline the near zone of the explosion, the zone of inelastic ground deformations.

Table 2

Wave	q, kg	$\bar{r}$, m/kg$^{1/3}$	Oscillation-recording duration, sec	T^{vis}, sec	T^{max}, sec	f^{vis}, hertz	f^{max}, hertz	$\Delta f/j^{max}$, %
			Kazakhstan					
K_z	10^4	2.31	0.595	0.460	0.740	2.17	1.35	119
	10^3	2.50	0.555	0.340	0.345	2.94	2.90	110
	10^3*	2.50	0.445	0.280	0.475	3.57	2.10	120
	120	2.54	0.475	0.440	--	2.27	--	--
K_x	10^4	2.31	0.655	0.600	0.740	1.67	1.35	119
	10^3	2.50	0.535	0.460	0.715	2.17	1.40	130
	10^3*	2.50	0.525	0.380	0.690	2.63	1.45	120
	120	2.54	0.475	0.440	0.605	2.27	1.65	118
P	10^4	9.25	0.160	0.260	--	3.85	--	--
	--	--	--	0.132	--	7.37	--	--
	10^3	10.00	0.070	0.128	--	7.80	--	--
	10^3*	10.00	0.075	0.200	--	5.00	--	--
	120	8.13	0.040	0.084	--	11.90	--	--
	10^4	19.20	0.175	0.100	0.208	10.00	4.78	--
	10^3	20.00	0.100	0.112	--	8.90	--	--
	10^3*	20.00	0.090	0.200	--	5.00	--	--
	120	19.30	0.075	0.072	--	13.90	--	--
	--	--	--	0.120	--	8.35	--	--
R	10^4	19.20	0.875	0.550	0.590	1.82	1.70	44
	10^3	20.00	0.500	0.240	0.300	4.17	3.35	88
	10^3*	20.00	0.470	0.250	0.308	4.00	3.25	81
	120	19.30	0.260	0.240	0.312	4.17	3.20	118
			Moscow area					
K_z	330	3.62	0.510	0.430	0.590	2.33	1.70	114
	120	4.20	0.445	0.420	0.512	2.38	1.95	113
K_x	330	3.62	0.570	0.380	0.590	2.63	1.70	114
	120	4.20	0.435	0.310	0.490	3.22	2.05	114
P	10^3	9.10	0.090	0.200	--	5.00	--	--
	330	9.75	0.067	0.160	--	6.25	--	--
	120	10.00	0.057	0.140	--	7.15	--	--
R	10^3	9.10	0.625	0.390	0.480	2.56	2.10	76
	330	9.75	0.740	0.330	0.480	3.03	2.10	86
	120	10.00	0.360	0.200	0.455	5.00	2.20	98

*Explosions set off on site I.

According to some studies [17 and 18] for example, the inelastic zone includes rock-crushing regions, ring fractures and radiating cracks and the residual deformation zone extending to the boundary beyond which the law of linear relationship between ground deformation and stress becomes operative.

The seismic indications of the near zone are the increasing diminution of the displacement amplitudes and velocities of the particles with distance [10, 11, 19, 20]. The time of the growing displacement (on a free surface) to a maximum point also diminishes with increasing r. The changes of the particle oscillation rates in the near zone are governed by the energy theory of similarity. The law of gravity produces a pronounced effect on the displacement of particles. Observations within the medium (in a mine) have shown that the propagation of an elastic compression wave is accompanied by low-frequency ground oscillations which is interpreted as an inelastic (plastic) movement of the medium.* According to the seismic data, the radius of the inelastic zone in clay and loam is $6 \div 8 \sqrt[3]{q}$.

Let us examine the changing spectra of the R wave and the total K movement with increasing distance.

Fig. 2 shows the spectra of seven explosions at various distances. The spectrum levels are relative: in the case of the same corrected distance $\bar{r} = r/\sqrt[3]{q}$ all the explosion spectra are located on the same level which makes it easier to observe their changes by increasing the distance from the source as well as the weight of the explosive charge. A comparison of the curves reveals that the spectra of the camouflet explosions in the Moscow area are narrower than the similar spectra in Kazakhstan (by about 10-20 percent), and the maximum frequency is confined to the 1.5-2.2 hertz interval. The maximum spectral frequency of the ejective explosions change within a wider range -- from 1.5 to 4.5 hertz.

In the case of ejective explosions the spectra of the total movement ($\bar{r} = 1.5 \div 2.5$ m/kg$^{1/3}$) have a lower frequency than those of the surface waves. But in camouflet explosions signals K (near the source) and R ($\bar{r} = 20 \div 30$ m/kg$^{1/3}$) have similar frequencies.

Let us follow the changing maximum frequency of the spectra of the total movement and surface wave with increasing corrected distance $\bar{r}$ (Fig. 3). In the near zone of the explosion, the area of the dome-shaped ground uplift, the maximum spectral cycle decreases with increasing distance and the frequency increases prior to the division of the waves into body and surface waves, whereas outside this zone ($\bar{r}$ = 10, 20, 30) the maximum cycle of the surface wave increases. The existence of a minimum cycle is noted where the zones join.

*See article by N. V. Kuz'mina in this collection.

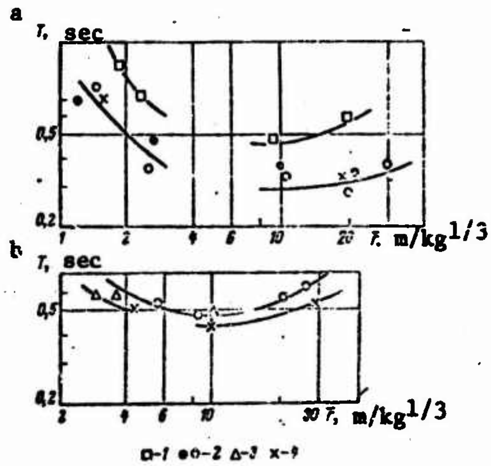

Fig. 3. Relationship curve of the peak spectrum of surface wave K ($\bar{r}$ = 5.6 ÷ 30) and the total K movement ($\bar{r}$ = 1.5 ÷ 4) and the corrected distance: a -- ejective explosions; b -- camouflet explosions; 1 -- q ≈ 10^4 kg; 2 -- q = 10^3 kg; 3 -- q = 330 kg; 4 -- q = 120 kg.

The existence of two different explosion zones is confirmed by the diagrams showing the relationship between the spectral amplitudes of the fixed total movement K and wave R, on the one hand, and the corrected distance, on the other (Fig. 4). The nature of the changing amplitudes of the spectral components by various $\bar{r}$ attributed to the values of these components at the shortest distance $\left|\frac{S_i}{S_i}\right|^{K,R}_{max}$ with increasing $\bar{r}$, varies in the near zone and outside it. Thus the amplitudes of all the observable frequencies of the ground movement K near the epicenter attenuate with distance less often than at a greater distance from the explosion, and the amplitude of the higher frequency attenuates slower with distance. In the R wave the diminution of the amplitude with increasing $\bar{r}$ is smoother in all the observable frequencies, and the component of the higher-frequency spectrum decreases at a faster rate.

Unlike these results, a number of studies, such as [13 and 21] for example, show that in a spectral analysis of the recordings the near zone of the explosion is singled out only in the diagrams showing a decrease of the full energy with distance.

With the frequencies fixed according to $\bar{r}$, the ratio of the spectrum ordinates near the explosion site decreases if the numerator of that ratio consists of a lower-frequency spectral component. But in the area where

the R wave is recorded the amplitude ratio increases. Consequently, the frequency of the surface wave becomes lower with increasing distance.

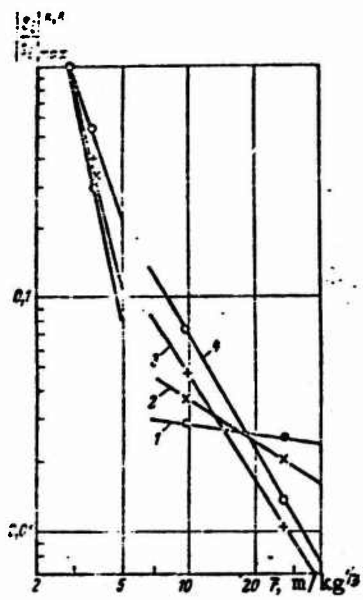

Fig. 4. Dependence of spectrum amplitude of the fixed frequency of the total K movement and wave R on the corrected distance in the explosion of a 330 kg charge at a depth of 18.6 meters: 1 -- 1.5 hertz; 2 -- 2 hertz; 3 -- 2.5 hertz; 4 -- 3 hertz.

The following spectral criteria of the near zone of the explosion have thus been obtained on the basis of the R and K wave spectra.

1. The maximum spectral frequency of the total movement increases with increasing $\bar{r}$. Beyond the zone the f^{max} magnitude is displaced into the region of lower values.

2. The diminution of the amplitudes of the spectral components with distance is governed by the exponential law $1/r^{n(f)}$, where the power indicator is a function of the frequency. The nature of the amplitude changes is different in the near zone and outside. In the total movement K the amplitudes of the observable frequencies attenuate with distance at a more rapid rate. The relation between the h value and the weight of the charge is noted in the case of certain explosions.

3. In the R wave the component of the lower-frequency spectrum decreases with distance at a slower rate, whereas in the total movement K near the explosion site a reverse relationship is observable -- the lower-frequency amplitude diminishes with distance at a faster rate.

The corrected radius of the near zone of the explosion in the $5 < \bar{r} < 10$ interval is outlined on the basis of the spectral analysis made at certain points of the profile.

The body wave spectra changing with distance. The spectra of the longitudinal wave displacement have one basic maximum in the zero frequency region. The second maximum of the spectrum is observable at frequencies over 10 hertz, its amplitude being lower than that of the first maximum by approximately one order. An exception to this is an explosion of a charge weighing 10^4 kg whereby $\frac{|S_i|\ \mathrm{I\,max}}{|S_i|\ \mathrm{II\,max}} \approx 4$.

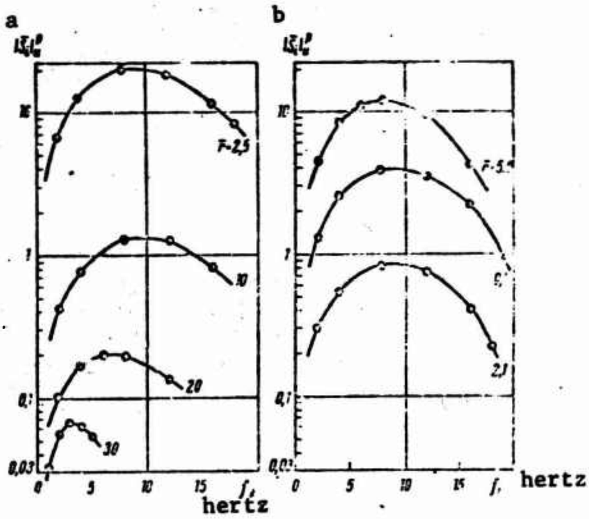

Fig. 5. Dependence of the frequency spectra of body wave p displacement velocities on the corrected distance: a -- ejective explosion in Kazakhstan; b -- camouflet explosion in the Moscow area.

Let us examine the changing spectra of the displacement velocities of the basic maximum of wave p, depending on $\bar{r}$, in the case of charges weighing 10^3 kg (Fig. 5). The plotting of the amplitudes took the recording scale into account.

The amplitude level of the spectra decreasing with increasing $\bar{r}$, and the form of the spectrum changes. The spectra of the particle velocity make it possible to follow the maximum frequency f^{max} which at first increases with the growing $\bar{r}$, but drops from 10 to 3 hertz on the 100-300 meter section. In the case of the explosions in Kazakhstan, the relative width of the velocity spectra increases with distance from 100 to 140 percent. In the Moscow area explosions the $\Delta f/f^{max}$ magnitude is not affected by $\bar{r}$ and amounts to 100-105 percent.

A decreasing amplitude of the lower-frequency spectral component, which later increases, is observable also in the case of longitudinal waves up to a certain distance from the source. A spectral analysis of the p wave, depending on the distance, facilitates an outline of the near zone of the explosion in addition to the R and K waves.

The changing p wave frequency with distance can hardly be followed visually in the explosion recordings [10]. Consequently, the effective absorption ratio of the longitudinal wave can be estimated only by way of a spectral analysis of the recordings made at different distances from the site of the explosion [22].

The effect of excitation on the frequency spectrum of surface and body waves. In this case the excitation of the oscillations implies the effect of the mechanical properties of the medium in which the explosions took place, on their seismic results. The displacement velocity spectra of the p and R waves were examined at the same distance from the eipcenter of three explosions of charges weighing 10^3 kg for each group of waves (Fig. 6).

A comparison of the velocity spectra of the ground particles should take into account the fact that the explosions took place not only in different grounds but also at different depths. The highest spectrum level was obtained in the case of a camouflet explosion in morainic loam ($h = 28.4$ m); further down are the levels of the ejective explosion spectra in clay and silty loam, respectively. The spectra of the p wave generated by all explosions have approximately the same relative width, whereas the spectrum of the R wave produced by a camouflet explosion is 10 percent narrower and displaced into the lower-frequency region.

It may be assumed that the difference between the R wave spectra is due to the dissimilar structure of the upper layers of the medium on these sites. And if that is so, the phase spectra (and dispersion curves) of the surface wave should be distinguished accordingly. Indeed the dispersion curves were found to be different. A change of the cycle from 0.1 to 0.6 sec produces a greater change in the phase velocities in Kazakhstan than in the Moscow area (Fig. 7). The phase velocities determined by a hodograph for the visible recording period ($T^{vis} = 0.2 \div 0.25$ and 0.38 sec), are well in keeping with the dispersion curves. It is conceivable that the resulting

dispersion curves are indicative of the different depth structures of the explosion sites within the first 100 meters, and the R wave spectra reflect that difference.

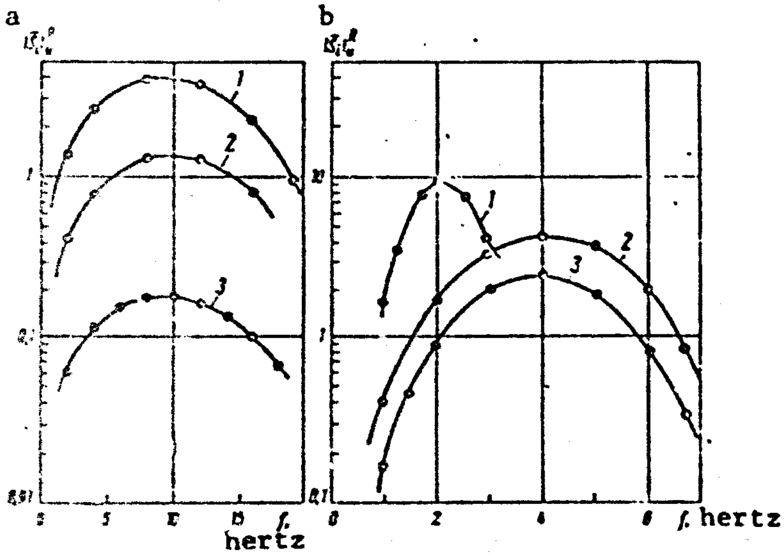

Fig. 6. Displacement velocity spectra of ground particle in the p wave (a) at a distance of r = 100 meters from the epicenter, and in the R wave (b) at a distance of r = 200 when the explosions are set off by charges weighing 10^3 kg: 1 -- camouflet explosion in morainic loam, h = 28.4 meters; 2 -- ejective explosion in clay, h = 5 meters; ditto in silty loam.

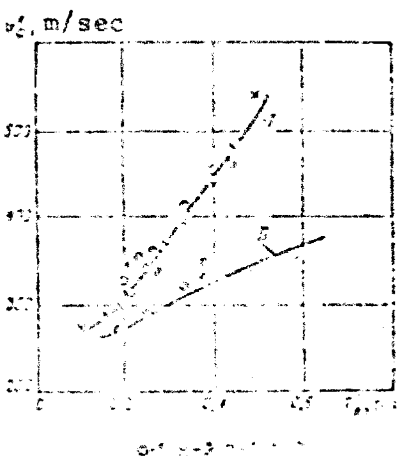

Fig. 7. Dispersion curves of the phase velocity of the R wave in Kazakhstan (I) and in the Moscow area (II) plotted on the basis of the phase spectra of these waves, with $\bar{r} = 10 \div 20$: 1 — q = 100 kg; 2 — q = 120 kg; 3 — q = 1000 kg; 4 -- phase velocities defined by hodograph for the visible period.

The frequency spectra of the two ejective explosions (h = 5 meters) differ only by their amplitude level. The width of the spectrum and maximum frequency of both of them are practically the same despite the fact that one explosion was set off in clay and the other in silty loam. For the p wave $f^{max} = 9.5 \div 10$ hertz and the relative width of the spectra is $\Delta f/f^{max} = 100$ percent; in the case of the surface wave $f^{max} = 4$ hertz and $\Delta f/f^{max} = 60$ percent.

A comparison of these explosions by the highest coordinate of the velocity spectrum shows that the seismic effect of the explosion in clay is seven times greater than in loam when estimated on the basis of the longitudinal wave, and 1.8 times greater if reckoned by the surface wave. The particle velocity ratios of 5 and 1.8, determined by the empirical relationship between the u_p^2 and u_R^2 magnitudes and the distance appear to conform to the spectral analysis data.

The considerable change of the explosion effect, when estimated by the p wave, is apparently due to the mechanism governing the formation of the body wave at the source. Plastic clay facilitates the change of the explosion energy to a longitudinal wave, whereas in silty loam the body wave is considerably weaker [10].

Thus the amplitude level of the spectra depends on the mechanical properties of the ground in which the explosions take place. The width of the spectrum and its peak shift along the frequency axis are determined by the depth of the source and the structure of the site.

The effect of the charge weight on the frequency spectrum of the seismic oscillations. The effect of the weight of the explosive charge on the oscillations is discussed in greater detail in studies [23 and 24] in which the spectra of the ground oscillations produced by explosive charges of different weights were compared at the same point. A quantitative analysis of the spectra revealed that in the case of a fixed P wave frequency, the function $|S_1| = f(q)$ has an area of a sharply rising spectral amplitude and a "saturation" area [23 and 24], and the lower-frequency components of the spectrum reach the saturation area when heavy charges are exploded.

Unlike the above-listed studies, the completed investigation included comparison of the ground oscillation spectra in the p and R waves and total movement K in the same corrected depths h. Such a comparison made sense as the parameters of the ground oscillations (the amplitudes of particle displacements and velocities, the time in which the displacements reach their peak and the duration of the oscillations) are usually investigated at the corrected points $\bar{r}$ in the case of a scale series of explosions [10, 11, 19].

The effect of the charge weight on the oscillation spectra is discussed separately for the ground movement in the epicentral region and the p and R waves.

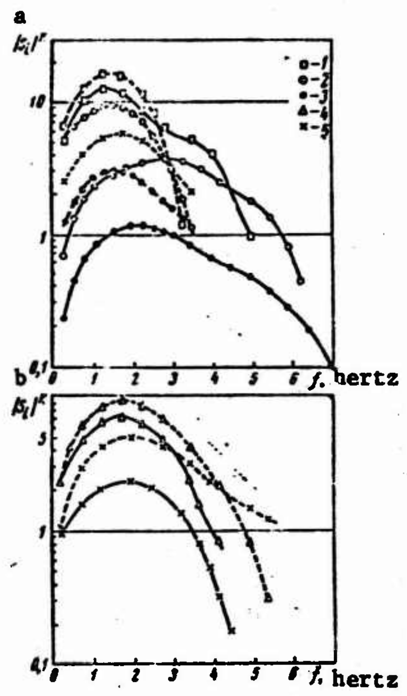

Fig. 8. Frequency spectra of the total ground movement produced the explosion of charges of different weight: a -- ejective explosions ($\overline{r}$ = 2.5); b -- camouflet explosions ($\overline{r}$ = 4); 1 -- q = 10^4 kg; 2 -- q = 10^3 kg (site II); 3 -- q = 10^3 kg (site I); 4 -- q = 330 kg; 5 -- q = 120 kg; broken line indicates x-component, the solid line -- z-component.

The near zone. The frequency spectra of the total ground movements for both components (z and x) are cited in Fig. 8. In camouflet explosions the maximum frequency of the spectrum on these components is the same and amounts to 1.75 hertz, with q = 330 kg, and 2 hertz with q = 120 kg, and the relative width of the $\Delta f/f^{max}$ spectra (at the 0.7 level) is 115 percent.

The relative steepness calculated for the right-hand spectrum gradient was defined from the following expression

$$\eta_{i-k} = \frac{\lg|S|' - \lg|S|''}{\lg f' - \lg f''} .$$

Indexes i-k indicate the frequency interval to which this definition applies. It is impossible to judge the shape of the left gradient of the spectra as

the recording of all the waves with a frequency of 1.5 hertz and lower is subject to apparatus-related distortions.

In the explosion of the charge weighing 330 kg the η_{3-4} magnitude of the x and z components is -2.7 and -3.06 respectively, and when a 120 kg charge is set off the figures are -1.93 and -1.63, that is if the charge is heavier the right spectrum gradient of the total movement is steeper.

The horizontal component of the ground movement produced by ejective explosions has a lower frequency (see Fig. 8, a). Thus when a charge weighing q = 1000 kg is exploded on site II, f^{max} = 1.4 hertz (x) and 2.9 hertz (z), and on site I f^{max} = 1.5 hertz (x) and 2.12 hertz (z). The relative width of the spectrum is 110-130 percent. The expansion of the z-component spectrum into the area of higher frequencies is due to the fact that body wave p is among the first to reach those distances.

As the weight of the charge increases, the peak of the x-component spectrum shifts slightly to the low frequencies. The steepness of the right spectrum gradient increases.

q, kg	120	10^3	10^4
f^{max}, hertz	1.65	1.4	1.3
$\eta_{2.5-3.5}$	-2.17	-4.32	-7.3

It follows from Fig. 8 that the amplitude level of all the spectra rises with the increasing weight of the explosive charge, and on the adopted distances the amplitude of the horizontal movement (x) is higher than that of the vertical (z).

The p wave. The changing amplitude level and shape of the displacement and velocity spectra of the ground particle in the longitudinal wave p with the increasing weight of the charge is shown in Fig. 9.

The longitudinal wave spectra are characterized by the presence of a second maximum at frequencies above 10 hertz. The second peak is apparently produced by the oscillations in the p wave which are superposed on the lower-frequency particle movement in the body wave, and these oscillations are increasingly manifested with an increasing charge [10]. As the weight of the charge is increased, the frequency of the first as well as the second peak of the oscillation spectrum shifts to the area of lower frequencies, and the steepness of the right gradient increases. When a charge weighing q = 10^4 kg is exploded, the amplitude of the second maximum of the velocity spectrum is higher than that of the first.

Table 3 shows the frequency and relative width of the velocity spectrum as well as the η values characterizing the steepness of the displacement spectrum in the frequency range of 6-10 hertz in the Kazakhstan explosions, and in the frequency range of 10-16 hertz in the Moscow area explosions.

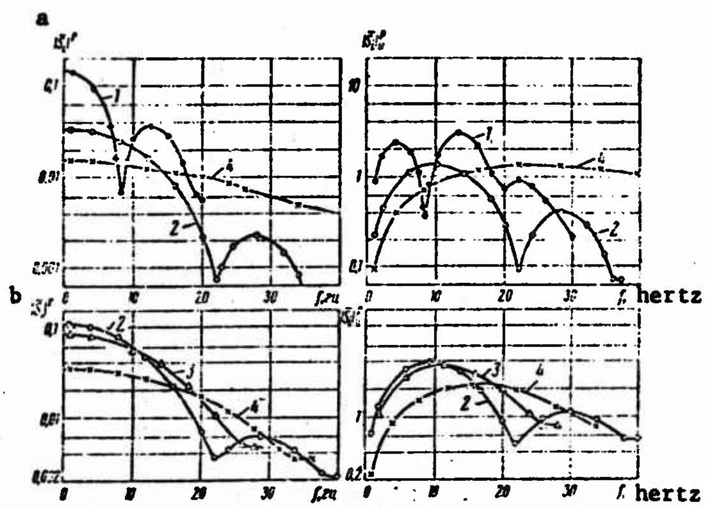

Fig. 9. Frequency spectra of the displacements and velocities of the ground particles in the p wave in explosion of different weight charges at corrected distance $\bar{r}$ = 10: a -- ejective explosions; b -- camouflet explosions; 1 -- q = 10^4 kg; 2 = q = 10^3 kg; 3 -- q = 330 kg; 4 -- q = 120 kg.

Table 3

Indexes	Explosion site						
	Kazakhstan				Moscow Area		
q, kg	120	10^3	10^3	10^4	120	330	10^3
f_u^{max}, hertz	23	9.5	10	4	16.8	11.6	9.4
$\frac{\Delta f}{f_u^{max}}$, %	--	100	102	108	104	108	102
η	-0.19	-0.71	-0.56	-7.65	-0.52	-1.37	-2.29

In the explosions set off by charges of the same weight the frequency of the maximum velocity spectrum of the ground particles in the Moscow area is displaced to the area of lower values, as compared to Kazakhstan.

The p wave spectra reflect the different structure of the sites down to the discontinuity boundary, the underside of the low-velocity layer, that

is the deeper the discontinuity boundary, the lower the recording frequency of the p wave. The visible frequency of the p waves increases with the growth depth of the explosion on each site [10, 11].

The R wave. The weight of the explosive charge also affects the changing amplitude and shape of the surface wave displacement spectrum (see Fig. 2). As the weight of the charge increases, the f^{max} shift slightly to the left, with the exception of an explosion set off by a charge weighing 10^4 kg. In the latter case the type of recording and nature of the dispersion [10] are different than in other explosions.

An increase in the weight of the charge results in a reduction of the relative width of the spectrum. The η and $\Delta f/f^{max}$ values on the 0.7 level of the maximum amplitude are cited in Table 4.

Table 4

Indexes	Explosion site						
	Kazakhstan				Moscow Area		
q, kg	120	10^3	10^3	10^4	120	330	10^3
η	-1.57	-7.37	-7.37	-8.1	-2.13	-1.95	-3.87
$\frac{\Delta f}{f^{max}}$, %	115	78	90	43	90	85	70
i-k, hertz	5.5-6.5	5.5-6.5	5.5-6.5	2-3	3-3.5	3-3.5	3-3.5

The use of the corrected distances in the description of the oscillation spectra resulting from explosions of varying force has revealed that the spectra of the p and R waves and total K movement vary at the points of $\bar{r} = r/\sqrt[3]{q}$. This difference is probably due to the following.

The velocity and displacement amplitudes of the ground particles changing with the distance and weight of the explosive charge can be expressed by the following exponential function [10, 11]

$$a = M\left(\frac{\sqrt[3]{q}}{r}\right)^n \text{ or } a = M\frac{q^m}{r^n},$$

where M is some constant magnitude.

The m and n exponents of the visible recording frequency of each wave are practically constant (the m_{vis} values are shown in Table 5, the n exponent of the body wave equals two and the surface wave 1-1.35). The amplitudes at the corrected points are approximately equal. The two similar distances r_1 and r_2 are determined in the explosions of charges weighing q_1 and q_2 from the following expressions:

$$\frac{r_1}{r_2} = \left(\frac{q_1}{q_2}\right)^{1/3} \text{ or } \left(\frac{q_1}{q_2}\right)^{m/n} .$$

According to the visual observations, the m/n ratio is close to 1/3 and, consequently, the similarity is satisfied. A study of the oscillation spectra has shown that the n and m magnitudes are functions of the frequency and weight of the explosive charge [23]. Consequently, in the case of different spectral components of the signal the m/n ratio will be different, and the similarity will not be satisfied.

Table 5

Type of wave	Site	$m_{\lvert S\rvert max}$	m_{vis}
p	Kazakhstan	1.20	0.76
	Moscow Area	1.10	0.73
R	Kazakhstan	0.85	0.33
	Moscow Area	0.65	0.43

The effect of the explosive charge weight on the spectra of the p and R waves has also been investigated at one point (r = 200 and 47 meters). The resulting data (on three explosions) have facilitated a rough estimate of the changing frequency and amplitude of the spectrum peak with the changing weight of charge q. Thus in the case of the p and R waves produced by the explosions in Kazakhstan the relationship was found to be $f^{max} = Mq^{-1/3}$ which conforms well with the visual observations [10, 20, 25].

Near the source, however, the deviation of this dependence with the increasing q magnitude from the theory [8, 26] requires further study.

The changing amplitude of the longitudinal wave spectrum with the changing weight of the explosive charge is theoretically described by an exponential function in which m = 2/3 is the exponent [8, 9]. This value of index m is close to the 0.73-0.76 magnitude found empirically for the first displacement of the p wave beyond the inelastic zone ($a_p^z \approx q^{0.73-0.76}$)

and the congruence of the particle velocity amplitude with the theory is practically complete ($\bar{u}_p \approx q^{0.63-0.67}$) [10, 11]. The values of exponent $m|S|_{max}$ for the amplitude of the p and R wave displacement spectrum are shown in Table 5. It also shows the visual values m_{vis} for the first displacement of the p wave and the highest amplitude of the R wave. It follows from the table that the m values of the amplitudes defined by visual observations are lower, whereas the f^{vis} values based on the same data are higher (see Table 2).

The following observations will elaborate this table.

1. An analysis of the frequency spectra of the ground oscillation in the near zone of the explosion has revealed that the form of the spectra is a simple one, and that it has one pronounced maximum in the 1.2-2 hertz frequency region. The frequency of the maximum is 30-50 percent lower than the visible frequency of the dome-shaped ground uplift.

2. A spectral analysis of the ground displacements, depending on the distance, makes it possible to outline the near zone of the explosion, the zone of inelastic ground deformations.

3. The frequency spectra of the oscillation generated by ejective explosions differ from the analogical spectra of camouflet explosions by width, amplitude and maximum frequency. The relative width of the R wave spectra in camouflet explosions is 10-20 percent less than in ejective explosions, and the highest frequency of the spectrum changes within the ranges of 1.5-2.2 and 1.7-4.6 hertz respectively. The disparity between the highest frequency of the spectrum and the visible frequency is 20-30 percent. The displacement velocity spectra of the longitudinal wave produce the changes in the frequency of the spectrum peak, depending on the weight of the charge, in the following intervals: from 9 to 17 hertz in camouflet explosions, and from 4 to 23 hertz in ejective explosions.

4. Two ejective explosions of the same force set off at a depth of 5 m in grounds with different mechanical properties will have similar oscillation spectra at the same distance; the latter, however, will be displaced along the axis of the amplitude. The seismic effect of explosions in clay is greater than in loess-like loam (5-7 times in the p wave and approximately twice in the R wave).

5. The increasing weight of the explosive charge is accompanied by a rising amplitude of the spectra of all waves and a changing form of the spectrum: the right gradient becomes steeper and the maximum frequency of the K and p wave spectrum shifts to the area of lower values. A decrease in the relative width of the spectrum with the increasing weight of the explosive charge is observable in the case of the R wave.

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ABSTRACT

Analysis of frequency spectra for ground oscillations in the near zone of an explosion indicates a simple shape with a simple well-defined maximum at 1.2-2 hertz. The frequency of the maximum is but two-thirds to one-half the apparent frequency of the domal uplift of the ground. Analysis of soil displacement relative to distance makes it possible to outline the near zone of the explosion, where nonelastic deformation takes place. The frequency spectra from eruptive explosions differ from similar spectra of underground (confined) explosions in width, amplitude, and frequency of the maximum. The relative width of the R-wave spectrum for confined explosions is about 80 to 90 percent that for explosions with ejected material. The frequencies of the maximums are 1.5-2.2 and 1.7-4.6 hertz, respectively. Frequency of the spectral maximum differs from the visible frequency by 20-30 percent. The velocity spectra for longitudinal waves change in frequency of the maximum, depending on size of charge: from 9 to 17 hertz for confined underground explosions, from 4 to 23 hertz for cratering explosions (with ejecta). It was found that the seismic effect in clay is greater than in loessial loam. With increase in size of charge, the amplitude of all waves increases and the shape of the spectrum alters. [AT8032902]

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